Flying New Technology on a "Faster, Better, Cheaper" Deep Space Mission

David H. Lehman, Leslie L. Livesay, Marc D. Rayman, Philip Varghese, Ralph R. Basilio

Deep Space 1 (DS1), launched on October 24, 1998, was the first mission of NASA's New Millennium program. DS1 was one of NASA's "faster, better, cheaper" missions chartered to flight test twelve high-risk, advanced technologies important for future space and Earth science programs on both a fast schedule and a low budget.

Concept studies of the Deep Space 1 (DS1) project were initiated in July of 1995 and the spacecraft was launched in October 1998. DS1's prime mission was successfully completed in September of 1999. Advanced technologies flight-tested during the mission included ion propulsion, high-power solar concentrator arrays, three on-board autonomy technologies, two low-mass science instrument packages, and several telecommunications and microelectronics devices. Among its firsts, DS1 was the first deep space mission to use ion propulsion to actually go somewhere (asteroid Braille in July of 1999) and the first mission to use a totally autonomous on-board navigation system. In addition, another of its autonomous systems, called the Remote Agent Experiment, was awarded NASA's 1999 Software of the Year award.

The authors were members of the project management team throughout DS1's development and operations phase, and we experienced all the "ups and downs" of the project. At its peak this $152M project employed over 200 people, all of whom had to be efficiently employed to ensure everything "got done" when it had to "be done." To the credit of the DS1 team, in this day and age of large overruns and long delays on the typical complex aerospace system development, the project not only exceeded its mission success criteria, but had only a 3-½ month delay in launch (which did not affect the achievement of its technical objectives) and 6% cost overrun with respect to the original project cost/schedule constraints. This was achieved in the face of numerous setbacks and problems with getting high-risk, high-payoff technologies (with large unknowns at the beginning) ready to launch in a short period; plus the spacecraft had to survive the rigors of launch and the radiation and temperature environment of deep space. Throughout the development and launch of the spacecraft and its mission operations phase, the project team had to deal with the paradox of developing and operating "high-risk technologies" on a short fused schedule at relatively low cost on a mission that the customer wanted with little to no chance of failure.

This paper will describe the mission and technology aspects of DS1 and the key lessons learned on this "faster, better, cheaper" technology validation project.

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Agenda

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- New Millennium program
- Mission summary
- Technology payload
- Technology testing results
- Technology benefit example
- Braille encounter summary
- Key lessons learned
- Summary

References:

[1] Rayman, M.D., Varghese, P., Lehman, D.H., Livesay, L.L., "Results from the Deep Space 1 Technology Validation Mission," Acta Astronautica 47, p. 475 (2000).

[2] Laufer, A., "Simultaneous Management - Managing Projects in a Dynamic Environment," AMACOM (1997).

[3] Lehman, D.H., Livesay, L.L., Rayman, M.D., Varghese, P., "Experience in Managing a 'Faster, Better, Cheaper' Project," Proceeding of the Project Management Institute Annual Seminars & Symposium, September 7-16, 2000, Houston, TX, USA.

Deep Space 1
Launched October 24, 1998
(http://nmp.jpl.nasa.gov/ds1/)

DEEP SPACE 1
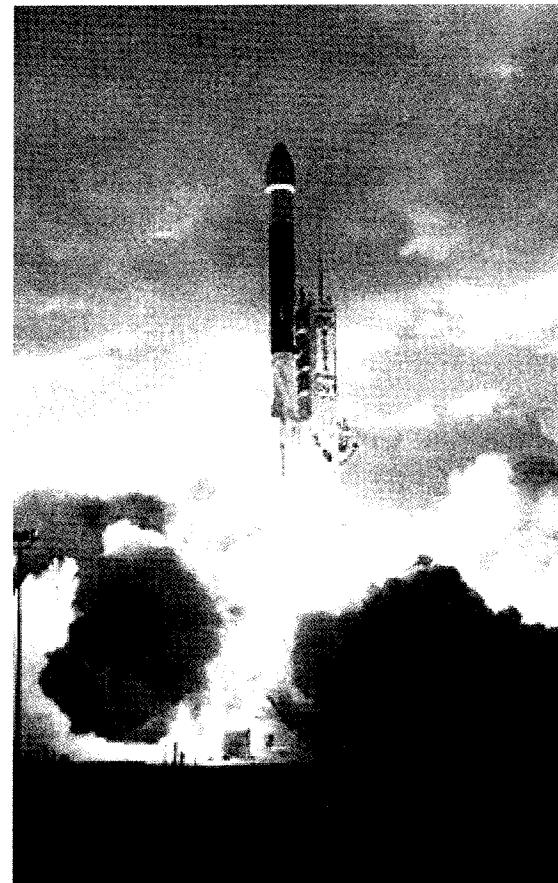
NEW MILLENNIUM

Boeing Delta II launch vehicle lifts off with DS1

New Millennium Program

JPL

Objective:

- Flight validate advanced technologies to help enable NASA's vision of Space and Earth science programs.

Technology selection criteria:

- Present a high risk to the first user and require in-flight validation.

- Reduce cost and risk of future programs.

- Represent a significant improvement over state of the art.

Technology validation:

- Assess the applicability of the technology product to those programs.

  - Elucidating the limitations of an advanced technology is valuable.

- Diagnose in-flight anomalies.

Deep Space 1 Mission Summary JPL

- DS1 was part of the New Millennium Program.
  - Mantra was to flight test in deep space high-risk/high payoff advanced technologies.
- DS1 was a cost-capped, schedule-driven, technology validation project, designed to flight validate 12 advanced technologies that represent major breakthroughs over state-of-the-art systems.
- Mission highlights:
  - Short development time: Project started in July 1995. 2 months pre-project, 36 months development.
  - Launch vehicle: Delta 7326.
  - Launch date was October 24, 1998 from Cape Canaveral Air Force Station.
  - Achieved minimum mission success criteria in December 1998.
  - **Exceeded complete mission success criteria in July 1999.**
  - Flew by asteroid Braille in July 1999.
  - First deep space mission to use Solar Electric Propulsion.
  - First deep space mission to do autonomous on-board orbit determination and control.

Deep Space 1 Mission Summary (Cont'd.)

- Mission highlights: (Cont'd.)
  - Prime mission successfully completed in September 1999.
  - Extended mission as a flyby of comet Borrelly approved by NASA and started in September 1999 - closest approach set for September 2001.
  - Star tracker "failed" in November 1999.
  - Star tracker recovery completed in June 2000.
    - Required major reprogramming of on-board flight software.
  - Ion engine operating time of 4800 hours (200 days) sets long duration record in August 2000.
  - DS1 on course to flyby comet Borrelly as of September 2001.

DS1 System Overview

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Mission

- Twelve advanced technologies (high risk - high payoff) validated via an asteroid flyby "test track" profile

Technology Description	Technology Suppliers	Funding Sources
Ion Propulsion System	Hughes, Moog, Glenn, SAI, JPL	NASA, Moog, Hughes
SCARLET Solar Concentrator Array	AEC-Able, Tecstar, Glenn, Entech	BMDO, NASA
Small Deep Space Transponder	Motorola	NASA, Motorola
Ka-Band Solid State Power Amplifier	Lockheed Martin (LM), JPL	NASA, Lockheed Martin
Autonomous Remote Agent Architecture	ARC, CMU, TRW, JPL	NASA
Autonomous Onboard Navigation	JPL	NASA
Beacon Monitor Operations	JPL, Univ. of Colorado at Boulder	NASA
Miniature Integrated Camera Spectrometer	SSG, Rockwell, Univ. of Arizona, JPL	NASA, SSG
Miniature Ion and Electron Spectrometer	SwRI, LANL	NASA, SWRI
Low Power Electronics	Georgia Tech., USC, MIT Lincoln Lab	NASA
Power Activation and Switching Module	LM	NASA, Lockheed Martin
Multi-Functional Structures	AF/PL, LM	AF/PL, LM

Spacecraft

- 486kg injected mass - Spectrum Astro was industry partner for "partial-bus" spacecraft development
- Spacecraft integration done at JPL with a badgeless Spectrum Astro/JPL team

Launch Services

- Delta 7326

Ground Segment

- JPL multi-mission infrastructure with DS1-led operations team

Science

- Taken at appropriate times during the mission (cruise and encounters)

Technology Validation - 1998 & 1999

Technology	Oct - Dec	Jan - Mar	Apr	May	Jun	Jul	Aug	Sep
IPS	70	90	100	L	L	L	L	L
	70	**100**	**100**	**L**	**L**	**L**		
SCARLET	100	L	L	L	L	L	L	L
	100	**L**	**L**	**L**	**L**	**L**		
SDST	100	L	L	L	L	L	L	L
	100	**L**	**L**	**L**	**L**	**L**		
AutoNav	50	75	85	85	95	100	L	L
	25	**75**	**85**	**85**	**95**	**100**		
MICAS	50	75	75	100	L	L	L	L
	10	**75**	**75**	**100**	**L**	**L**		
PEPE	50	75	75	100	L	L		
	50	**75**	**75**	**100**	**L**	**L**		
K_a SSPA & K_a telecomm	75	100	L	L	L	L	L	L
	75	**100**	**L**	**L**	**L**	**L**		
BMOX		75	90	90	100	L	L	L
		75	**90**	**90**	**100**	**L**		
MFS		100	L	L	L	L	L	L
		100	**L**	**L**	**L**	**L**		
PASM		100	L	L	L	L	L	L
		100	**L**	**L**	**L**	**L**		
LPE		100	L	L	L	L	L	L
		100	**L**	**L**	**L**	**L**		
RA				100				
				100				

Plan (cum)
Actual (cum)

L = Lifetime validation for hardware; continued operations experience with software.

Mission Success Criteria
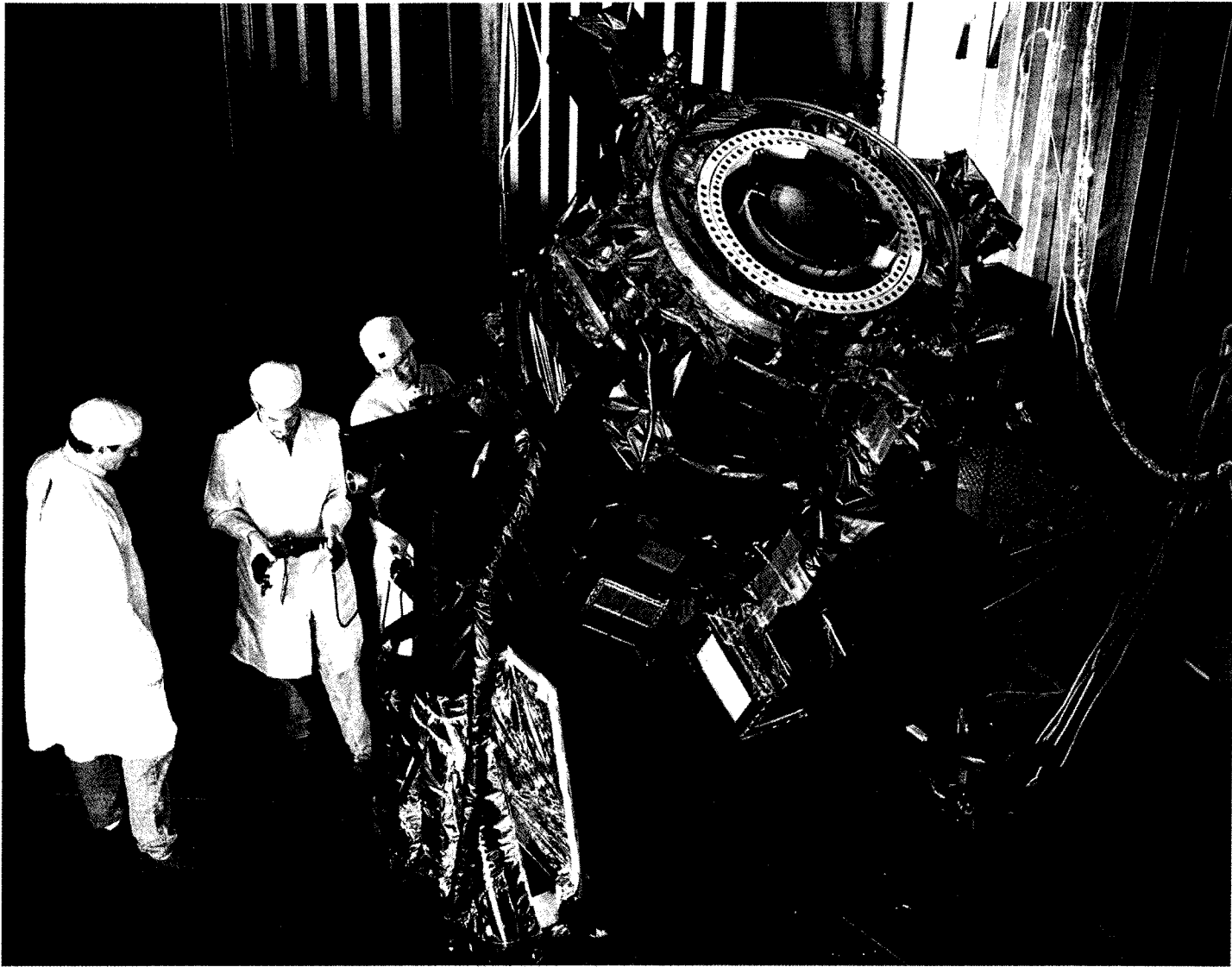
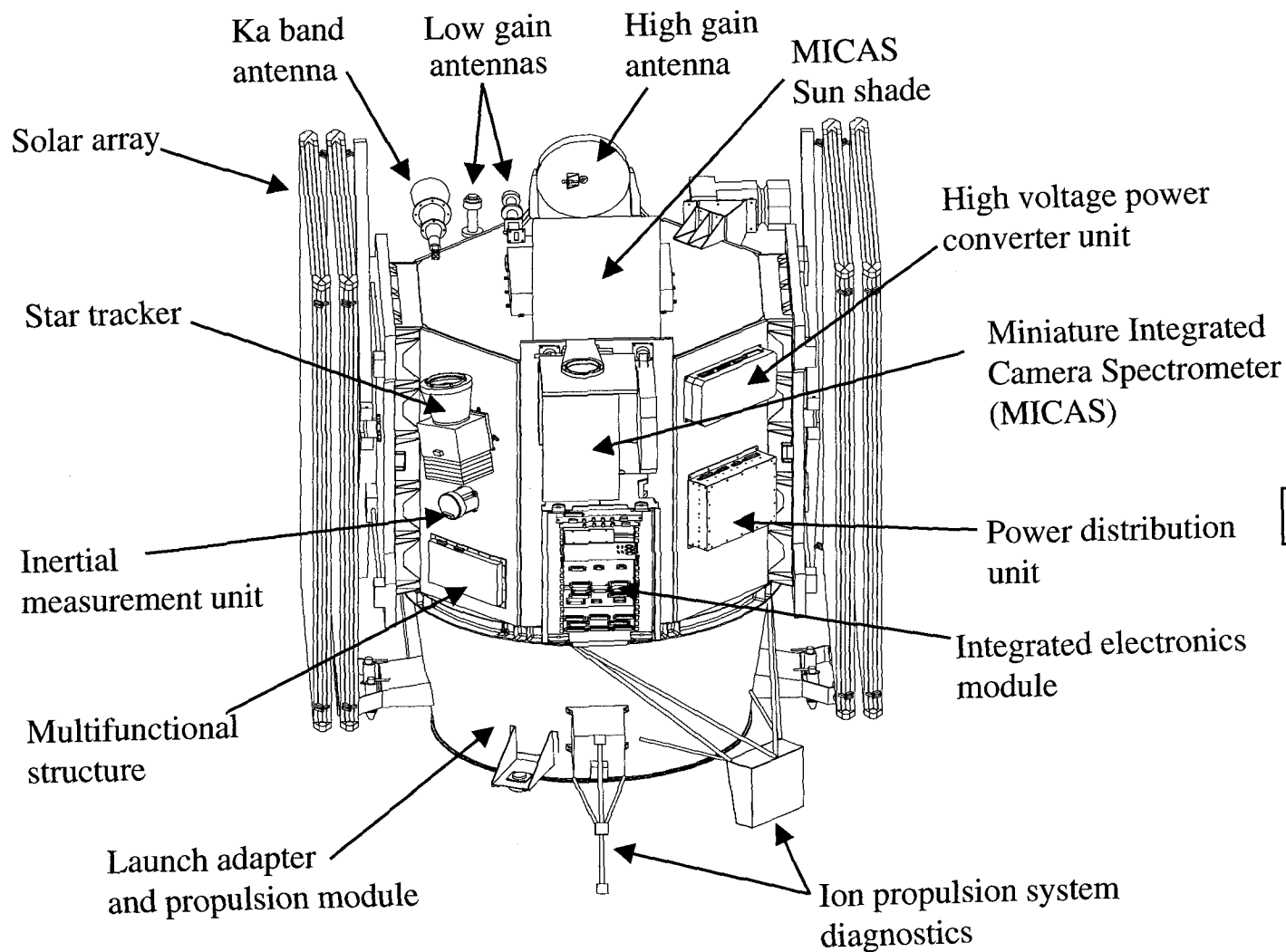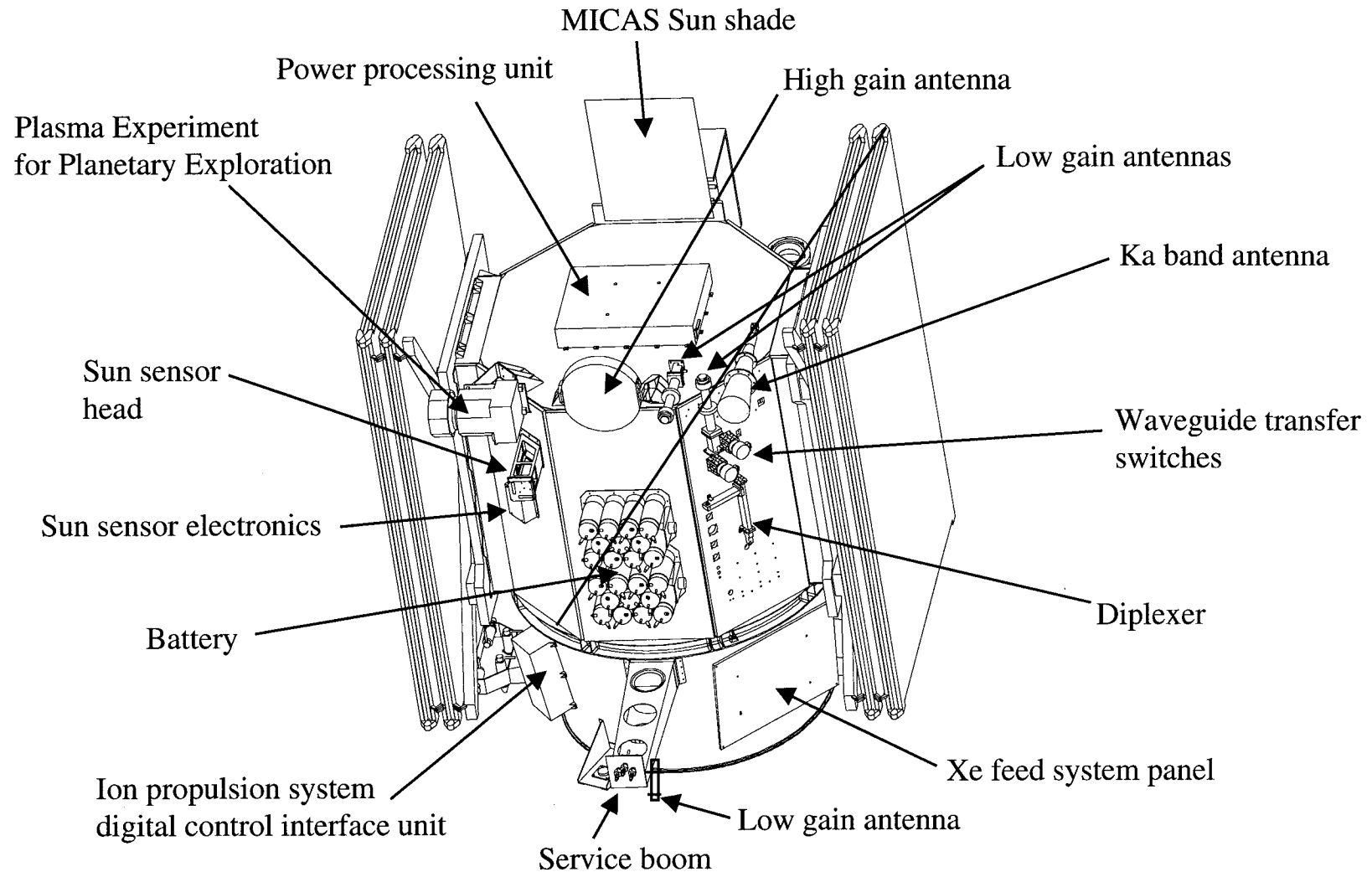| Status	Item
	1) Demonstrate the in-space flight operations and quantify the performance of the following 5 advanced technologies:
Complete	• Solar Electric Propulsion
Complete	• Scarlet Solar Concentrator Arrays
Complete	• Small Deep Space Transponder
Complete	• Miniature Camera and Imaging Spectrometer
Complete	• Autonomous Navigation
	and 3 of the 6 following advanced technologies:
Complete	• Beacon Monitor Operations
Complete	• Autonomous Remote Agent
Complete	• Ka-band Solid State Power Amplifier
Complete	• Low Power Electronics
Complete	• Multifunctional Structure [+ Plasma Experiment for Planetary
Complete	• Power Actuation and Switching Module Exploration (PEPE)]
Completed	2) Acquire the data necessary to quantify the performance of these advanced technologies by September 30, 1999. Analyze these data and disseminate the results to interested organizations/parties by March 1, 2000.
Complete	3) Utilize the on-board Solar Electric Propulsion (SEP) to propel the DS1 spacecraft on a trajectory that will encounter a near-Earth asteroid in FY 1999.
Complete	4) Assess the interaction of the SEP system operations with the spacecraft and its potential impact on charged particle, radio waves and plasma, and other science investigations on future SEP propelled deep space missions.

Deep Space 1

Ka band antenna

Low gain antennas

High gain antenna

MICAS Sun shade

Solar array

High voltage power converter unit

Star tracker

Miniature Integrated Camera Spectrometer (MICAS)

Inertial measurement unit

Power distribution unit

Multifunctional structure

Integrated electronics module

Launch adapter and propulsion module

Ion propulsion system diagnostics

1.5 m

Stowed Configuration

MICAS Sun shade

Power processing unit

High gain antenna

Plasma Experiment
for Planetary Exploration

Low gain antennas

Ka band antenna

Sun sensor
head

Waveguide transfer
switches

Sun sensor electronics

Diplexer

Battery

Ion propulsion system
digital control interface unit

Xe feed system panel

Low gain antenna

Service boom

New Millennium Program Deep Space 1
Successful Validation of 12 Breakthrough Technologies

- Ion Propulsion System: Enables rapid access to deep space
- AutoNav: First totally autonomous on-board navigation system
- Small Deep Space Transponder: Standard transponder for all follow-on deep space missions
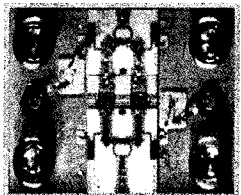- Remote Agent: NASA software of the year award
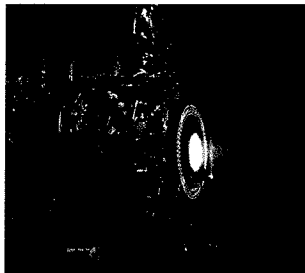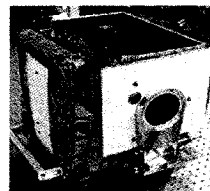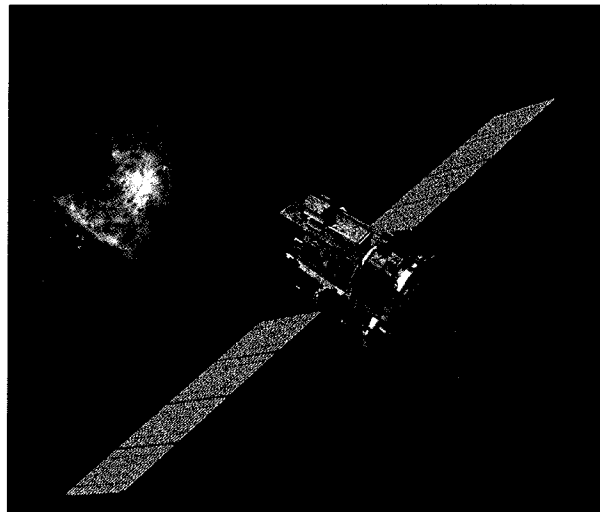

Small Deep Space Transponder
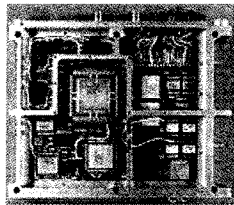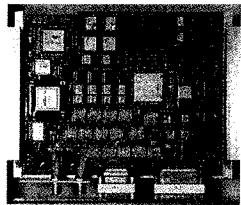
Remote Agent Architecture

Low Power Electronics

Miniature Integrated Camera Spectrometer

Plasma Experiment for Planetary Exploration

Ka-Band Solid State Power Amplifier

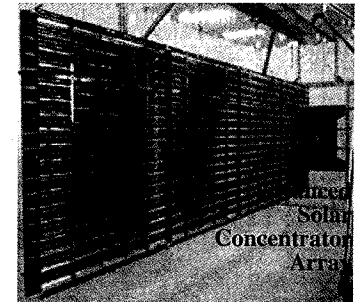**Power Activation & Switching Module**
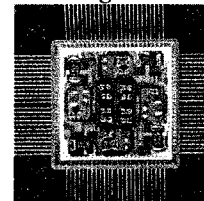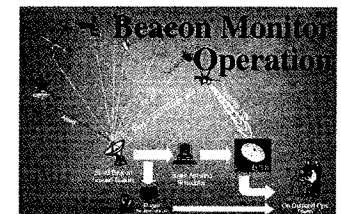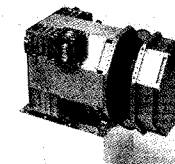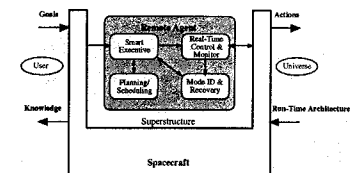
Autonomous Onboard Optical Navigation

Multifunctional Structure

DS1 Technology Payload

- Solar electric propulsion
  - Provided by NSTAR (NASA SEP Technology Applications and Readiness) Program
  - 2.5 kW $\leftrightarrow$ I_{sp} = 3100 s; throttle in discrete steps to 0.5 kW $\leftrightarrow$ I_{sp} = 1900 s
  - Diagnostics sensors for E and B, energy and density of electrons and ions, and surface contamination
- Solar concentrator array
  - Provided by BMDO
  - Arrays of cylindrical Fresnel lenses over strips of $GaInP_2/GaAs/Ge$
  - 2.5 kW at 1 AU BOL
- Miniature integrated ion and electron spectrometer
  - Energy and angle analysis for electrons and ions
  - Ion mass analysis
  - Microcalorimeter
- Miniature integrated camera and imaging spectrometer
  - 2 visible imaging channels (CCD and APS)
  - IR and UV imaging spectrometers
    - UV channel did not function correctly
  - Shared 10-cm primary mirror

DS1 Technology Payload - Cont'd.

- On-board autonomy
  - Optical navigation
  - Acquisition and processing of images of asteroids against stellar background
  - Orbit determination
  - Maneuver design and execution
  - Direct commanding of IPS, MICAS, and ACS
- Remote agent
  - Planner/scheduler to generate a set of activities
  - Executive to expand that to a sequence of commands and to monitor their xecution
  - Mode identification and reconfiguration
- Beacon monitor operations
  - Transmit 1 of 4 tones to indicate urgency of request for ground action. For example
    - No tracking required
    - Track when convenient
    - Track soon
    - Track as soon as possible
- Small deep-space transponder
  - X-band receiver, X-band and K_a-band exciters, CDU, TMU, and beacon tone generator
- K_a-band solid state power amplifier
  - 2.3 W RF, 13% efficiency

DS1 Technology Payload - Cont'd.

- Power actuation and switching module
  - Power switch using high-density interconnects with mixed signal ASIC controller
- Low power electronics
  - 0.9 V logic, 0.25 µm feature size
- Multifunctional structure
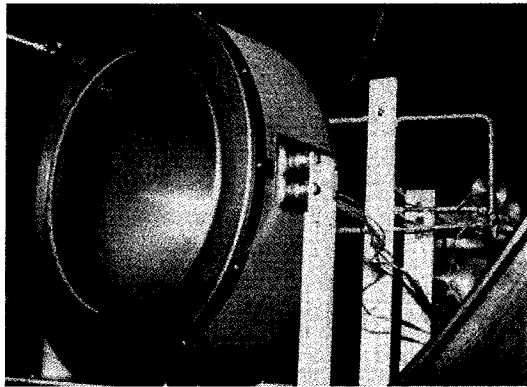 - Electronics integrated into load-bearing structural element
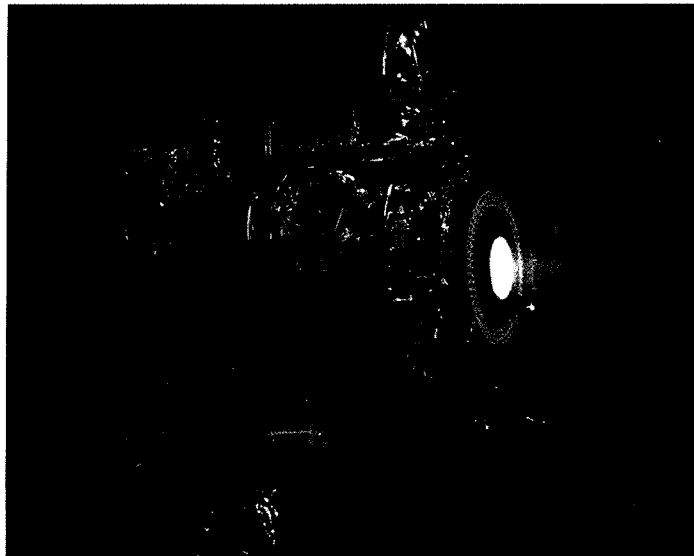
Technology Testing Results

Ion Propulsion System

Ion engine operating during end-to-end test as part of DS1 STV testing

Description

- Provided by NASA SEP Technology Applications & Readiness (NSTAR) Program

- 2.5 kW $\leftrightarrow$ I_{sp} = 3100 s; throttle in discrete steps to 0.5 kW $\leftrightarrow$ I_{sp} = 1900 s.

- Diagnostics sensors for measuring interactions with spacecraft and space plasma environment

Validation

- Demonstrate high efficiency operation

  - 31.25 kg expended to reach 1.9 km/s as of 9/18/00. Thrust is within 2% of prelaunch prediction

- Demonstrate reliable operation for at least 200 hours

  - 5600 hours of operation achieved as of 9/18/00

- Assess effects on spacecraft operation

  - All spacecraft systems operated normally during IPS thrusting. Telecommunications conducted routinely while thrusting and through beam.

Solar Concentrator Array
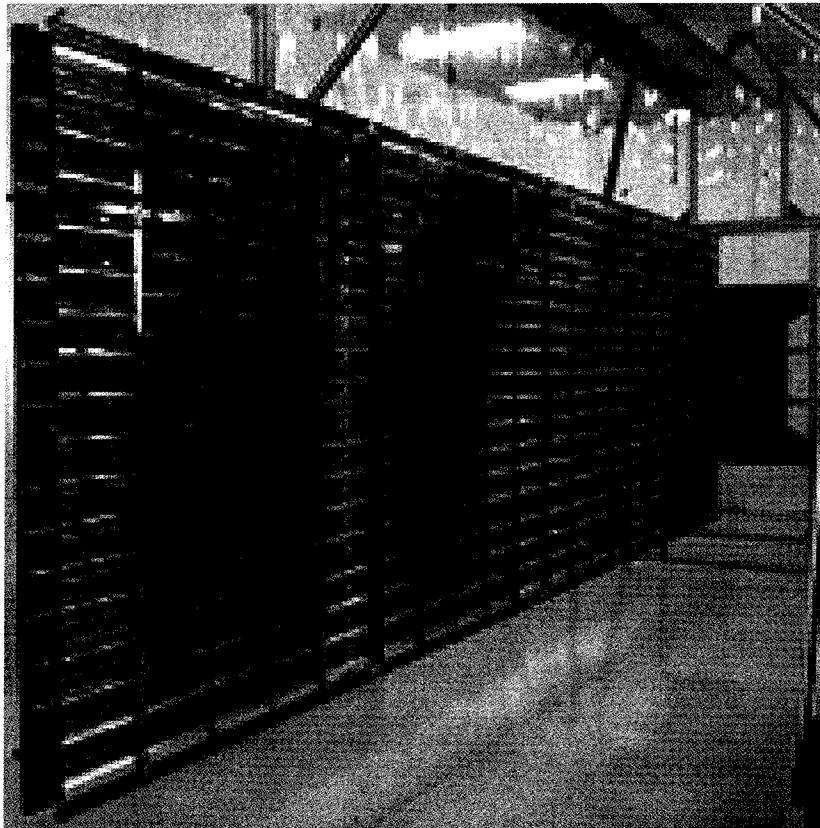
Description

- Provided by Ballistic Missile Defense Organization with support from NASA Glenn Research Center
  - Flight equipment delivered by industry
- Deployable concentrator array elements
  - Cylindrical Fresnel lenses over strips of $GaInP_2$/GaAs/Ge cells
- 2.5 kW at 1 AU (BOL)

Validation

- Demonstrate reliable deployment and stable operation
  - Alignment was so accurate, no pointing corrections were needed. Array operation stable throughout mission to date.
- Demonstrate high efficiency power generation
  - Cells operate at 22.5% optical-to-electrical efficiency.
- Validate prelaunch models of power generation capability
  - Power generation is about 1% higher than prelaunch prediction

Miniature Integrated Camera and Imaging Spectrometer
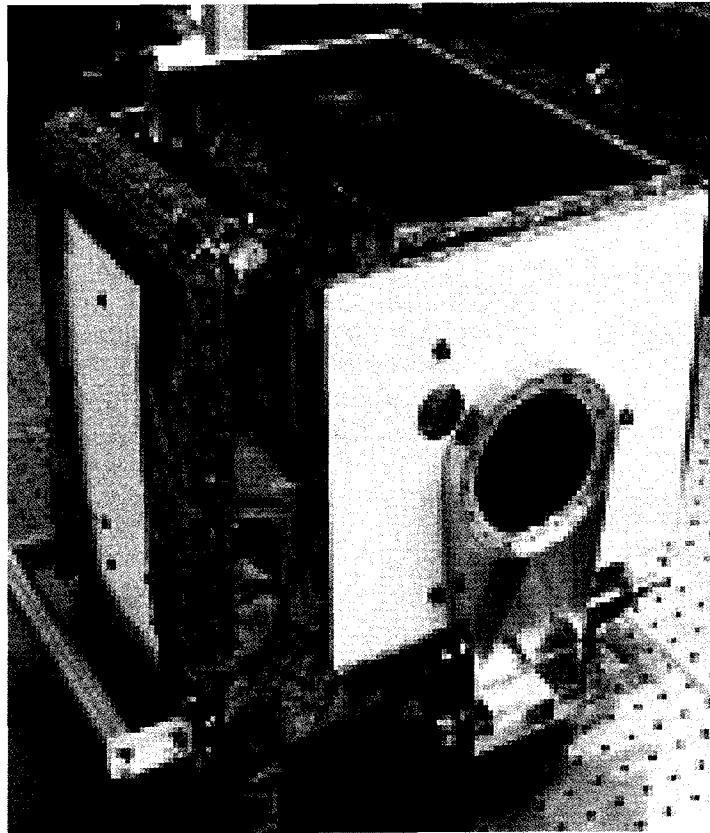
Description

- Fully integrated camera and imaging spectrometer, developed by USGS, SSG, Inc.,University of Arizona, Boston University, Rockwell, and JPL

  - Combines four different measurement capabilities into single instrument with common optics, electronics and structure
    - Two visible imaging channels
    - IR and UV imaging spectrometers
  - Silicon carbide optics & optical bench
  - Electronically shuttered visible channel eliminates need for moving parts

Validation

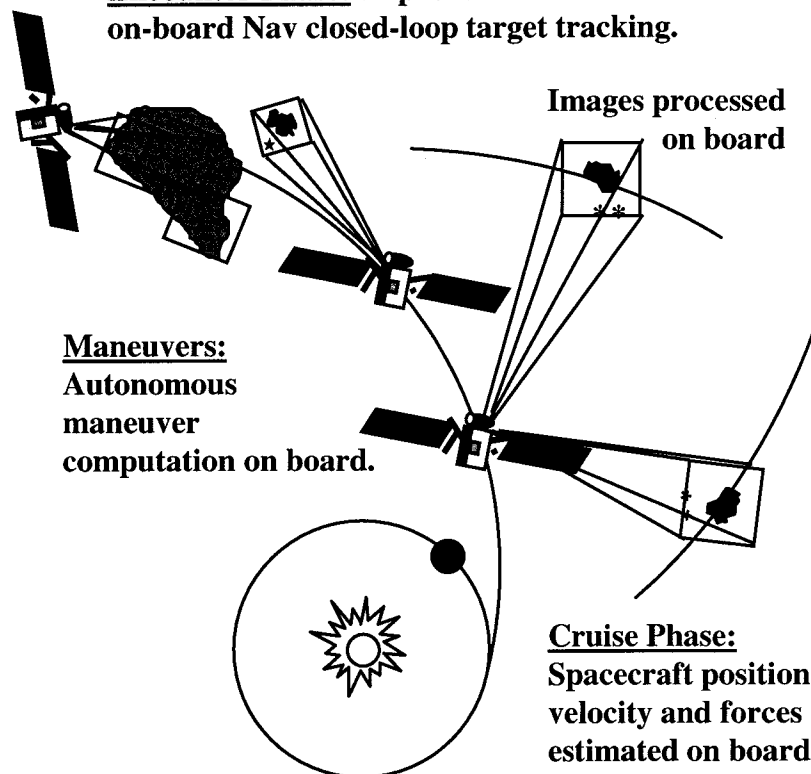- Demonstrate launch and integrity of silicon carbide bench
  - No in-flight changes in focus since final alignment before launch
- Demonstrate use of electronically shuttered visible channel (eliminating moving parts)
  - Used extensively for autonomous navigation imaging
- Demonstrate capability to return science-quality data
  - Calibrations conducted on 3 of 4 channels
  - UV channel did not work

Autonomous Navigation

Description

- Integrated autonomous optical navigation and trajectory control system

  - Uses images of asteroids, stars, and target bodies for orbit determination. Designs and executes maneuvers.

  - Direct commanding of IPS, MICAS, and ACS

Validation

- Demonstrate autonomous picture planning and sequencing

  - Autonomously turns spacecraft and images asteroids and stars

- Demonstrate autonomous orbit determination and maneuver planning

  - Autonomously processes pictures, determines orbit (~200 km accuracy, 0.15 km/s), and updates IPS thrust profile to keep on target for asteroid encounter

- Demonstrate autonomous control of IPS thrusting

  - Autonomously commands spacecraft attitude; pressurizes, starts, and stops IPS; updates throttle level and thrust attitude regularly.

- Approach delivery was 28.3 +/- 1.5 km (~1σ) from center of Braille.

Encounter Phase: Improved return of science with on-board Nav closed-loop target tracking.

Images processed on board

Maneuvers:
Autonomous maneuver computation on board.

Cruise Phase:
Spacecraft position, velocity and forces estimated on board

Miniature Integrated Ion and Electron Spectrometer
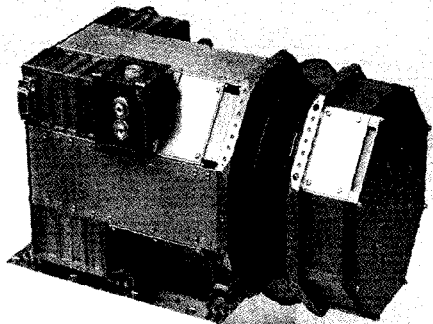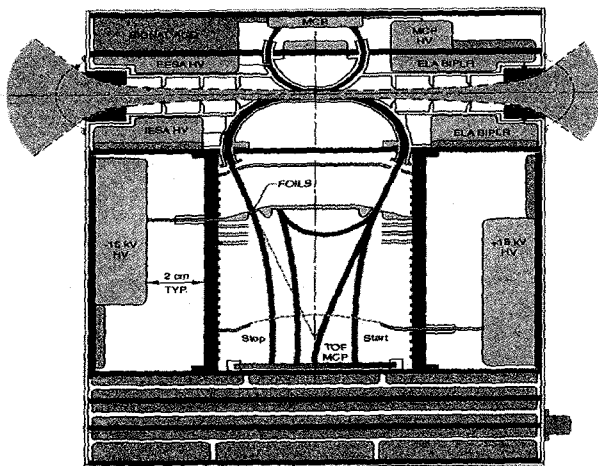
Description

- Combines multiple plasma physics instruments into one compact package
  - Energy and angle analysis for ions and electrons
  - Ion mass analysis
  - Very low power, low mass microcalorimeter

Validation

- Demonstrate ability to measure solar wind, even in presence of Xe plasma from IPS
  - Solar wind observations routinely conducted, including collaborative observations with Cassini Plasma Spectrometer

Beacon Monitor Operations

Description

- On-board system to monitor spacecraft health and safety, and request ground action when necessary
  - On-board health and safety data summarization
  - Tone transmission to indicate urgency of ground action

Validation

- Demonstrate detectability of beacon tones
  - Beacon signals detected under variety of signal conditions
- Demonstrate data summarization
  - Spacecraft data summarized and consistent with ground analysis

Remote Agent

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Remote Agent Architecture

Goals → Smart Executive, Real-Time Control & Monitor, Planning/Scheduling, Mode ID & Recovery — Remote Agent — Superstructure — Spacecraft — User — Knowledge — Actions — Universe — Run-Time Architect
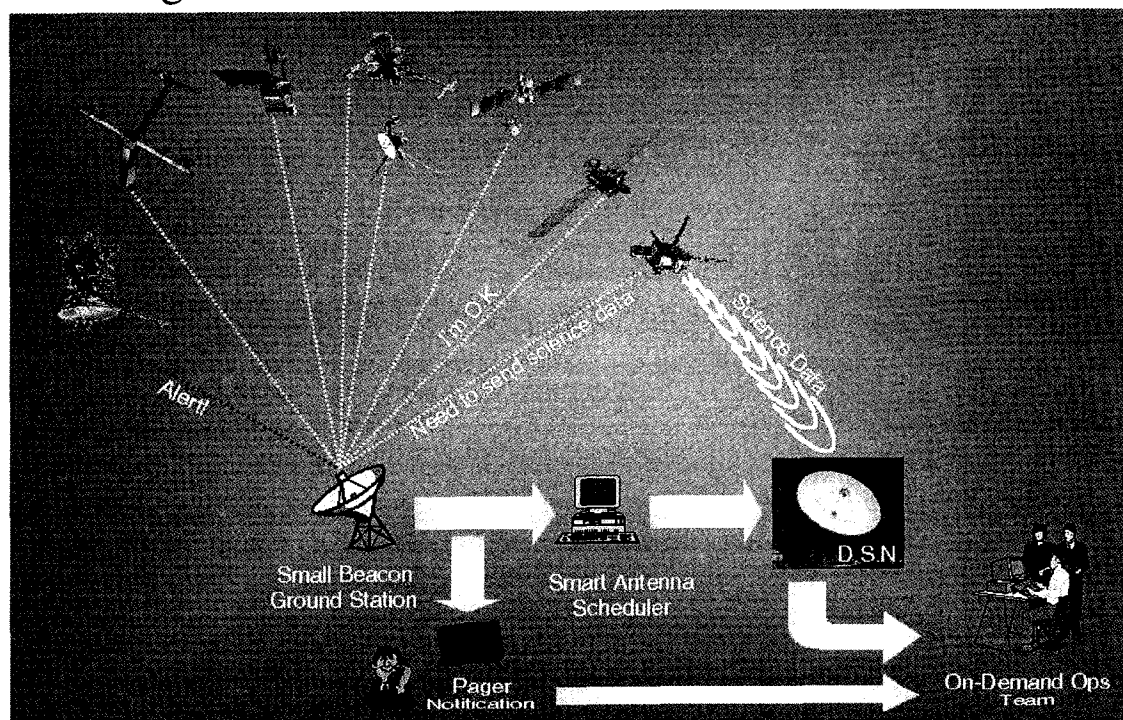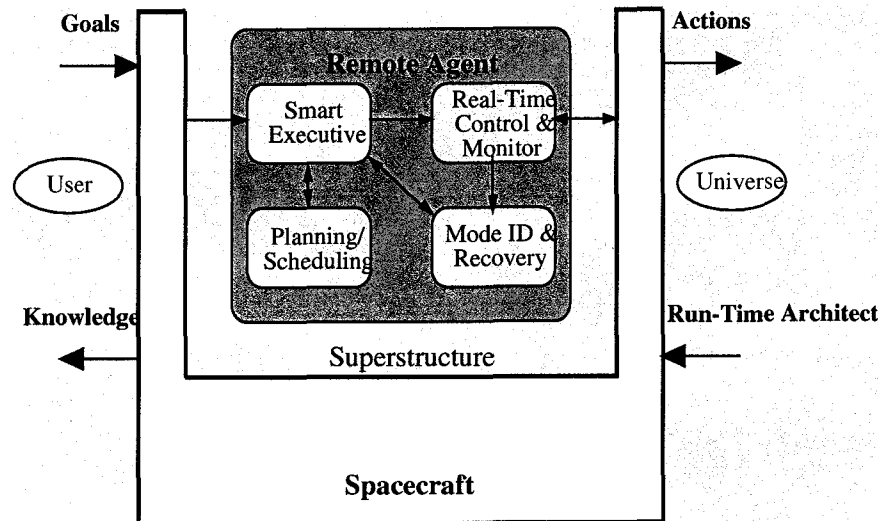
Description

- Autonomous "remote agent" that plans and executes on-board activities with only general direction from ground
  - Planner/scheduler to generate a set of activities
  - Executive to expand that into a sequence of commands and monitor their execution
  - Mode identification and reconfiguration to monitor spacecraft health and status

Validation

- Demonstrate on-board planning, execution, and handling of anomalies
  - Formulated and executed plans
  - Correctly handled all simulated failures, including need to replan

Telecommunications

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Small Deep Space Transponder

Description

- Compact, low-mass transponder that combines multiple subassemblies into a single unit
  - X-band receiver, X- and K_a-band exciters, command detector unit, telemetry modulation unit, and beacon tone generator

Validation

- Demonstrate reliable operation for communications (X-band uplink and downlink and K_a-band downlink), ranging (X and K_a), Doppler (X and K_a), tone generation (X and K_a)
  - All functions verified through routine use and dedicated experiments. All performance consistent with prelaunch predictions

K_a-Band Solid State Power Amplifier

Description

- Highest power solid state K_a-band amplifier ever used for deep space communications
  - Generates 2.3 W output with 13% overall efficiency

Validation

- Demonstrate functionality of unit and provide K_a-band signals for DSN and for communications and radiometrics performance assessments
  - Functionality verified
  - Signals used in technology development for upgrading DSN stations for K_a-band operation.
  - Communications performance in good agreement with models. Doppler and ranging in good agreement with X-band results.

Microelectronics

Low Power Electronics

Description

- 0.9 V logic, 0.25 μm gate lengths
  - Ring oscillator, multipliers, and discrete transistors

Validation

- Demonstrate radiation-resistant low-power devices in space environment
  - In-flight performance consistent with ground tests
  - Tests repeated each week during primary mission

Power Actuation and Switching Module

Description

- Power switch using high density interconnects with mixed signal ASIC controller

Validation

- Demonstrate operation of smart power switching and current monitoring in spacecraft power system
  - In-flight performance consistent with ground tests
  - Tests repeated each week during primary mission

Multifunctional Structure

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Formed Cover -
Shielding and Protection

MCMs

Copper Polyimide
Jumpers: Patch-to-Patch

Copper Polyimide
Jumper to Next
Panel

Copper Polyimide
Circuitry with MCM
Sockets and Surface
Mount Parts

Spacecraft Structural Panel with Integral
Thermal Control
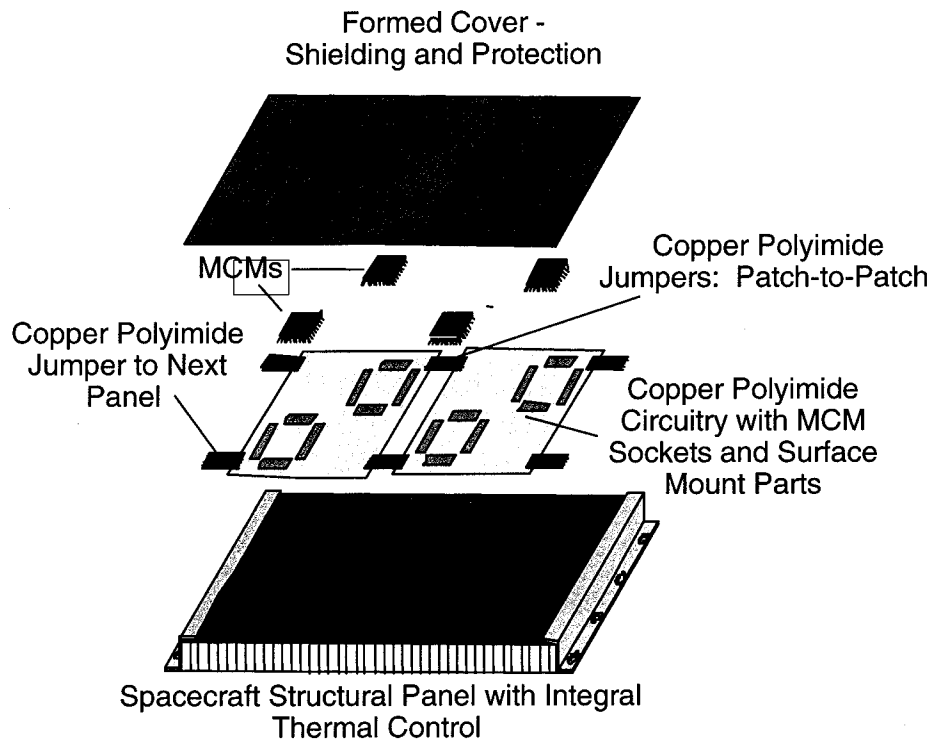
Description

- Integrates electronics into load-bearing structural element to reduce mass of spacecraft cabling and traditional chassis

Validation

- Demonstrate integration of electronics into spacecraft structure, with embedded thermal control

  - In-flight performance consistent with ground tests; no degradation observed during flight in flex connectors or multichip module sockets. Thermal gradients consistent with preflight predictions.

- With standard technology, DS1 would be ~3 times heavier / requires Delta III - class launch vehicle

- Conceptualized DS1 using standard technology with similar functionality/trajectory:
  - N_2O_4/MMH bipropellant propulsion system
  - Mars '98 - class telecom
  - Cassini-type plasma instrument
  - Cassini type visible / IR spectrometer
  - Scaled solar array
  - DS1 planned trajectory using total fuel

  DS1 ion propulsion and other technologies offer significant benefits to future missions

Injected Mass (kg)

~1,300

486

Old Tech DS1 Delta III class

DS1 Delta II (7326)
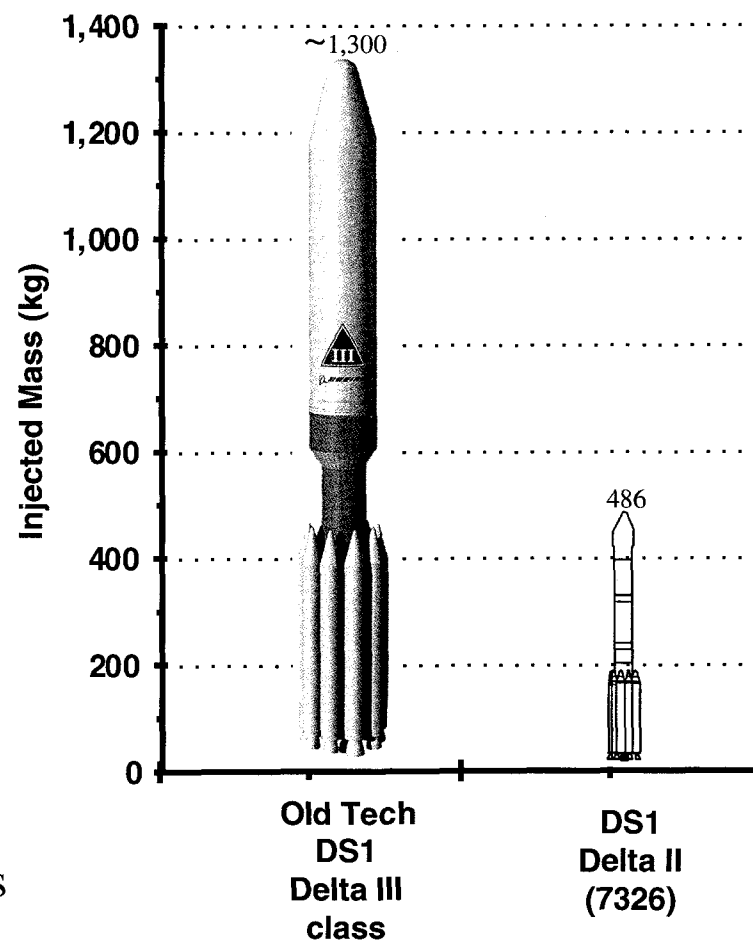
- Encounter occurred with Braille in July 1999.

- Encounter was a *bonus* science encounter for the mission.

- Encounter was closer than any other encounter ever attempted

  - 28.3 km from center of asteroid

- Science data collected:

  - All planned PEPE and IDS data was obtained.

  - Some visible and IR data collected.

  - Not as much as planned due to previously unknown (but now well understood) non-linearity in the camera response, combined with the asteroid being dimmer than the worst case prediction.

    - This prevented AutoNav from getting any pointing updates during the closest approach.

Key Lessons Learned

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- <u>Item #1</u>: DS1 had only a 2-month pre-project phase prior to initiation.
  - Not until a year after start could we finalize project objectives, success criteria and the project plan. This delay lead to many challenges for the project team, including the requirement for significant overtime, especially during the launch campaign.
  - <u>Lesson learned - Systematic and Integrated Planning</u>: Projects need a healthy pre-project in terms of funding and time to develop a project plan.
- <u>Item #2</u>: Early in the development, a key decision was required to de-manifest or descope two of the advanced technologies for the mission (3D Stack Advanced Flight Computer and the Remote Agent technologies).
  - The decision to do this was made months after it it had to be made
  - Late decision was a major contributor to our 3 month launch delay.
  - <u>Lesson learned - Timely Decisions Adjusted to Uncertainty</u>: For key issues, project managers must make sound and timely decisions.

Key Lessons Learned (Cont'd)

- <u>Item #3:</u> High risk items need a back-up plan. (Example - Remote Agent technology)

  - <u>Lesson Learned - Effective Risk Management</u>: Tasks with large uncertainty become the new critical paths of tomorrow if not effectively managed.

    - Don't let one rotten apple destabilize the entire plan.

- <u>Item #4:</u> Because of various factors, DS1 was not able to have acceptable margins at project start.

  - <u>Lesson learned - Effective Risk Management:</u> Good managers create reserves (or margins) at the beginning of a project as a means of absorbing uncertainty (or managing risk). Good margins are needed to protect against highly uncertain elements of the project.

Key Lessons Learned (Cont'd)

- Item #5: To make DS1 happen, we had to work hard to build effective partnerships with various organizations, both to keep costs down and to ensure a successful mission. These partnerships included items such as the main spacecraft bus, the launch vehicle, most of the technologies and their associated sponsors and lead engineers, and hardware from other NASA projects and other government agencies (US and foreign).
    - DS1 required 14 MOUs with its partners.
    - On a fast-paced project like DS1, this makes schedule management extremely difficult, because your partners don't always have the same skills, concerns, objectives or goals as you do.
    - The project manager should remember that the number of partners on a project is inversely related to the ability to control the "rudder" of the project. This means that the project manager has to work extra hard to build "effective" coalitions to keep the project team working smoothly together.
    - Lesson learned - Effective Leadership: "Leadership means coping with uncertainty and change. Managing means coping with complexity in stable conditions. Good project managers have to assume both roles, leadership and managerial. They are expected to do the right things (lead), and to do them right (manage). They see themselves as responsible for motivating the multiple internal and external participants of the project."[2]

Key Lessons Learned (Cont'd)

- <u>Item #6</u>: The DS1 organization included an Industry Partner with responsibility to deliver the core spacecraft bus. Our short schedule necessitated the team begin work on the design while defining roles and responsibilities, identifying team strengths and weaknesses, and developing a common language and understanding of institutional differences. This painful process could have been minimized if the core project team had taken the time up front to clearly define the teaming arrangement.

- <u>Item #7</u>: Early on, the project manager wanted to co-locate the needed parts of the team in one building to improve teamwork and to improve intra-team communications. However, this collocation was not a priority of the senior management and the collocation did not occur until 3 months prior to launch. This collocation helped immensely in increasing the rate of closing open issues and streamlining the process of operating the spacecraft after launch.

- <u>Item #8</u>: The project had many team lunches and after-work parties together; we also had numerous "all-hands" meetings to help develop the teamwork necessary in all successful projects. We worked hard to develop a "badge-less" environment for all our different partners.

- **<u>Lesson learned - Teamwork.</u> A project manager can never do enough to build a good team-working environment.**

Key Lessons Learned (Cont'd)

- <u>Item #9</u>: We did not have sufficient funding authority to fully fund the development of the spacecraft and ground system until 1 ½ years after project start.

  - The funding delay resulted in delays in the development of the hardware required for the flight and ground system.

  - The impact of this late delivery of funds was not felt until much later when we realized that we would have to delay the launch.

  - <u>Lesson learned - Adequate resources</u>: For FBC projects, the lesson learned is that because the phases of the project overlap so much, adequate funding is needed "up-front" to ensure success.

- <u>Item #10</u>: The mission operations development effort started work from day 1 of the project. We used the mission operations ground data system throughout the entire ATLO period. A large portion of the development team transferred directly into the operations phase of the mission. This resulted in a well trained operations team that knew how to fly the spacecraft well before launch.

  - <u>Lesson learned - Think about mission operations from day #1 of the development.</u>

- <u>Item #11:</u> After a year on the project, we finally settled upon a one-page level-1 project requirements document.
  - This document was easy to understand and it had both the key project requirements (including technical as well as the cost and schedule requirements) and goals.
    - The understanding with the customer was that the project goals could be dropped or de-scoped in order to meet the requirements if we ran into development problems.
  - This list was very helpful to the project and was easy to understand by most of the team.
  - <u>Lesson learned - Simple Procedures</u>. Use simple, easy to understand procedures, especially for critical documents.

Key Lessons Learned (Cont'd)

- <u>Event #12</u>: Though project management personnel understood the key requirements and goals of the project, not all team members did.
  - We thought we had effective and good communications to our team, but in our case it was not as good as we thought.
  - What was a goal to us was a requirement to certain team members who were responsible for one of the mission's experiments.
  - The project management did not do a sufficient job of explaining this to these team members - that it was possible to descope their part of the project to meet the requirements.
  - This lack of communications within the project team was a factor in the launch delay.
  - <u>Lesson learned - Communicate, Communicate, Communicate.</u> Use simple, easy to understand procedures and work to communicate them to the team.
    - "How well you communicate is determined by how well you are understood, not by how well you express yourself."[2]

Key Lessons Learned (Cont'd)   JPL

- <u>Item #13</u>: On DS1 we set up a set of technology readiness gates to track or gauge progress in their developments.
  - In some cases, we did not follow our early review plan and not all team members understood our approach to project monitoring.
  - This lack of systematic monitoring cost us in the long run because of down-stream schedule delays.
  - Because we paid so much attention to monitoring the new technologies on DS1, we paid less attention to the standard technologies on the spacecraft. This came to haunt us when the key power supply for the spacecraft was delivered 12 months late. This late delivery led directly to the spacecraft launching 3 months late.
  - <u>Lesson learned - effective peer reviews,</u> especially early in the development phase, would have likely caught the problems we had with the power supply and possibly other problems we had during the development phase.
    - "The need to monitor project performance is based upon the homegrown truth that identifying a small problem is difficult; correcting it is easy. Identifying a big problem is easy; correcting it is difficult."[2]
- <u>Item #14:</u> At launch, the minimum test time on the spacecraft electronics hardware was over 1000 hours.
  - <u>Lesson learned - Test, Test, Test.</u> Ensure your project has an adequate test plan and implement the plan.

Key Lessons Learned (Cont'd)

- <u>Item#15</u>: Many critics said that DS1 could not be done, especially in the early years.
  - It was too much to develop, launch and operate revolutionary technologies in such a short period of time on a shoestring budget.
- <u>Lesson learned - Perseverance</u> The key members of the project's staff and the majority of the project team stayed with the project from the beginning to the end of their assigned tasks and persevered in spite of many severe setbacks and at great personal sacrifice.
  - The perseverance of the team to get the job done, regardless of the obstacles (both from a technical and bureaucratic nature) was the key to our success.
- We hope that future projects will benefit from the lessons of managing DS1 so that they will not face the many problems DS1 encountered or will be able to weather them more smoothly.

<u>Summary</u>

- Deep Space 1 was an FBC project that flight tested in deep space twelve break-through technologies.

    - The mission <u>required</u> significant team heroics to make it happen.

- Exceeded technology validation for complete mission success in July '99. Deep Space 1 demonstrated:

    - New methods of propulsion for deep space,

    - New techniques of navigating through deep space,

    - New flight hardware that makes spacecraft much smaller, and

    - New capabilities to make spacecraft more autonomous; all of which provided

    - Significant potential benefits to future space science missions.

- DS1 is on course to flyby comet Borrelly in September 2001.

- IEEE Spectrum January 1999: "Last year ... may be remembered for what is arguably NASA's biggest breakthrough: The ion-propulsion system of the Deep Space 1."

- AIAA Aerospace Magazine, December 1999: "The NASA/JPL test bed called Deep Space 1 brought the most far-reaching results. DS1 space-tested a host of technological innovations, the showpiece being its high-efficiency ion engine. DS1 also demonstrated a level of autonomy never before attempted on a space probe."

ACS	Attitude Control System
AF/PL	Air Force – Phillips Laboratory
AIAA	American Institute of Aeronautics and Astronautics
ARC	Ames Research Center
ATLO	Assembly, Test, and Launch Operations
AU	Astronautical Unit
BMDO	Ballistic Missile Defense Organization
BOL	Beginning of Life
CDU	Command Detector Unit
CMU	Carneige Mellon University
DS1	Deep Space 1
FBC	Faster, Better, Cheaper
IDS	Ion Engine Diagnostic Sensor
IPS	Ion Propulsion System
IR	Infrared
IEEE	Institute of Electrical and Electronic Engineers
ISP	Specific Impulse
JPL	Jet Propulsion Laboratory
LANL	Los Alamos National Laboratory
LM	Lockheed-Martin
MICAS	Miniature Integrated Camera Spectrometer
MOU	Memorandum of Understanding

NASA	National Aeronautics and Space Administration
NSTAR	NASA SEP Technology Application's and Readiness Program
PEPE	Plasma Experiment for Planetary Exploration
RF	Radio Frequency
SAI	Spectrum Astro, Inc.
SEP	Solar Electric Propulsion
STV	Solar Thermal Vacuum
TMU	Telemetry Modulator Unit
USGS	United States Geological Survey
UV	Ultraviolet